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The benefit to aviation meteorology from radio occultation measurements using a combination of navigation satellites and airborne receivers

By R.W. Lunnon

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The benefit to aviation meteorology from radio occultation measurements using a combination of navigation satellites and airborne receivers

Abstract

It is well established that it is possible to derive information, predominantly humidity, from navigation satellite data (typically GPS) using receivers on the ground or polar orbiter satellites. A further possibility is to use receivers on aircraft. This study looks at the likely benefit to aviation from such technology. It shows that there are potential benefits in the forecasting of icing, fog, thunderstorms and contrails. However, there is considerable uncertainty in the accuracy of the data. Therefore the recommendation is that flight trials be conducted to assess the likely accuracy. However it is clear that the data coverage that could be provided throught this mechanism was sufficient to satisfy the requirements of the mesoscale model for humidity data.

This work was performed under contract to EUROCONTROL, contract number C20137E/NM/01.

1 Introduction

The first subsection of this introduction repeats the specification of the work. In answering the questions posed, it is necessary to describe operational Numerical Weather Prediction (NWP) and explain the way forecasts for aviation are produced. It was decided to approach this by having one section describing NWP in relatively general terms, followed by a section describing the outputs for civil aviation. This approach inevitably gives rise to a small amount of repetition. Later subsections of this introduction introduce the two major sections of the report. Subsequent sections of this report provide conclusions and recommendations for future work. Finally references and a list of acronyms are provided.

1.1 Specification of the work

Navigation satellites [referred to subsequently as GNSS, which stands for Global Navigation Satellite Systems], such as GPS [Global Positioning System], send signals through the atmosphere to their destination receivers. In so doing, they are subject to atmospheric delays. These delays are functions of several parameters that are relevant to meteorology. If the total atmospheric delay can be accurately measured, this can be used as an extra input to NWP models, thereby improving their performance.

The work will be to describe the benefits to aviation meteorology when total atmospheric delay data is available. The mechanisms by which the data is useful will be described. In particular the expected impact for icing, fog, fronts and thunderstorm forecasting will be addressed. When possible, quantitative relationships between the amount of data available, and the likely forecast improvements will be given.

In addition, the work will briefly describe the benefits to turbulence forecasting when measurements of turbulence on board aircraft are available.

1.2 Outline of forecasting chain

NWP models and the processes of profile retrieval and data assimilation, both of which have to be run in order to initialise the models, are computationally extremely complex. Consequently it is difficult to make statements which are both general and reliable about the impact of additional measured data on forecast accuracy. However it is possible to make some statements about the impact that changes in the inputs to each step of the chain have on the outputs from the step in question. It is also possible to make statements about the reliability of the connections that can be made. Therefore section 2 of this report describes briefly the individual steps in the chain, and gives indications of the impacts and the uncertainties in those impacts. Later in section 2 there are subsections which look at the consequences of making the most optimistic assumptions about the impact of the GNSS/aviation data on products for aviation, and the consequences of making more conservative assumptions.

1.3 The range of outputs for civil aviation

Atmospheric delay is a function of temperature, humidity and surface pressure (Healy and Eyre, 2000). The parameter which has most effect on delay is humidity, so it is logical in considering the outputs for civil aviation to focus on those which are most sensitive to humidity. In terms of aviation hazards, these include icing, fog and thunderstorms and these were explicitly mentioned in the formal specification of the work. These are covered explicitly in subsections of section 3.

In addition there is increasing concern about the effect of aviation on the environment (IPCC, 1999), in particular the possible effects of contrails and cirrus cloud sheets that might grow from these. Contrail formation is particularly sensitive to humidity so an additional subsection of section 3 addresses that.

Because of the complexity of NWP models an improvement in the initial values of humidity should give rise to an improvement in the forecasts of all parameters, and this issue is also addressed in section 3.

2 The forecast chain

2.1 Profiles of humidity

The impact of additional humidity profiles on the assimilated field of humidity depends on the number of additional profiles and the presumed accuracy of the profiles. If the actual accuracy of the profiles is poorer than the presumed accuracy, then there will still be an impact, but the ultimate impact on forecasts might be negative.

2.1.1 Accuracy of profiles

The expected accuracy of GNSS/aviation humidity profiles is subject to large uncertainty. According to Lesne and Haase (2001) "For high tangent point altitudes (near the 11 km flight altitude) the airplane velocity and position errors will induce the greatest errors in the retrieved refractivity profile." The working user requirement of a refractivity accuracy of 0.5% would require the velocity error to be reduced from 5mm/sec to 1mm/sec but it is by no means clear whether this can be achieved. Experiments will be required using specially equipped test aircraft (see section 5). However the accuracy of humidity retrievals from low earth orbit satellite GPS data is encouraging (Kursinski et al, 1997) so there are good grounds for optimism at least until flight tests can be conducted.

2.1.2 Number of profiles

It is relatively easy to quantify the likely number of retrievals - it is simply a problem in 4-dimensional geometry. There might be some value in addressing this issue rigorously, but the present project is simply a 1 dimensional study to get a quantitative feel for the likely distribution of occultations. The distribution can be used to quantify the impact of the data on the assimilated humidity field. The study considers an airline operator flying a number of different fleets of aircraft out of a single airport hub, and quantifies the density of retrieved profiles as a function of distance from that hub. In generating the figure it was assumed that the routes flown by each fleet were distributed isotropically (that is, the same in all directions). This is a highly artificial assumption but it was necessary in order to produce the plot.

Figure 1a shows the number of occultations per day per 100km flown as a function of distance from the hub airport. The details of how the figure was constructed are included in appendix 1.
As can be seen (and as would be expected) the density of occultations generally speaking decreases as distance from the hub increases (because aircraft never reach distances exceeding their range from the hub - cabotage is ignored). However there are occasional spikes on the graph from the extra occultations that arise as a result of ascents from and descents to the destination airports.
The number of occultations per day from an operator, ignoring those that arise as a result of ascents and descents, depends only on the number of aircraft in each fleet, the speed of the aircraft and the utilisation of the fleet. Major airlines such as British Airways publish information quantifying those variables for all their fleets, and in fact it was BA data that were used to generate figure 1a. An uncertainty is the number of flights flown by each fleet per day - this affects the distribution of occultations, but not the total number. If a fleet flies a large number of flights per day, then the occultations will be rather close to the hub airport, but if a lower number of flights are flown (by implication, longer routes) then the occultations will occur further from the hub. Figure 1a was generated using a maximum plausible number of flights (which vary with fleet): figure 1b was generated using the minimum plausible number of flights. As can be seen, the number of occultations per day per 100km lies between 240 and 560 for the zone up to 700km from the hub. The implications of this density are discussed below.

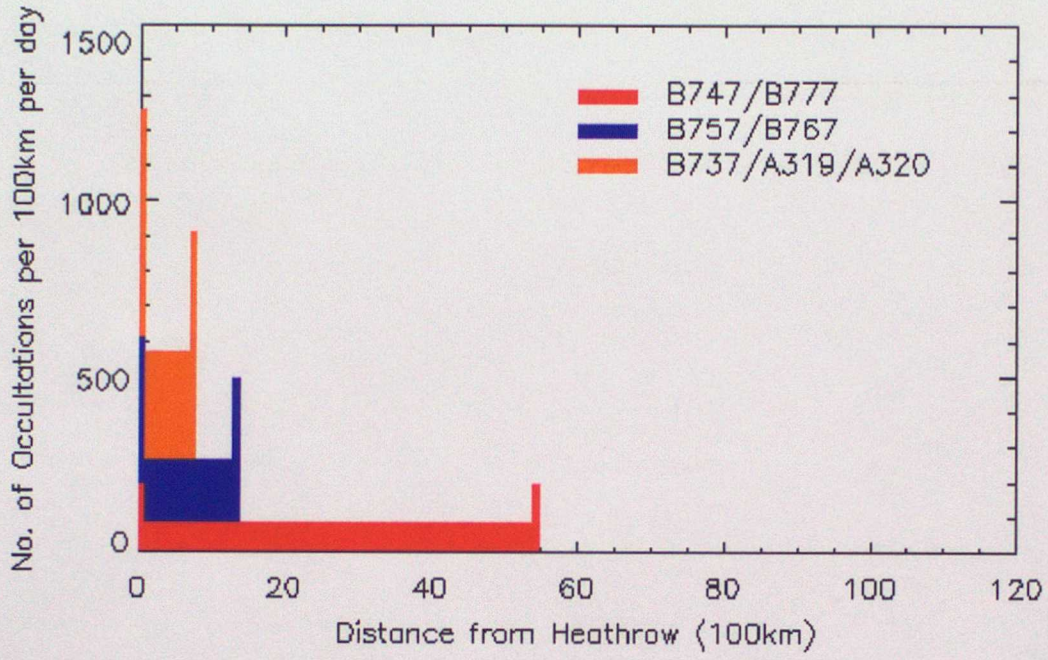

Figure 1a Density of occultations assuming maximum number of flights per day

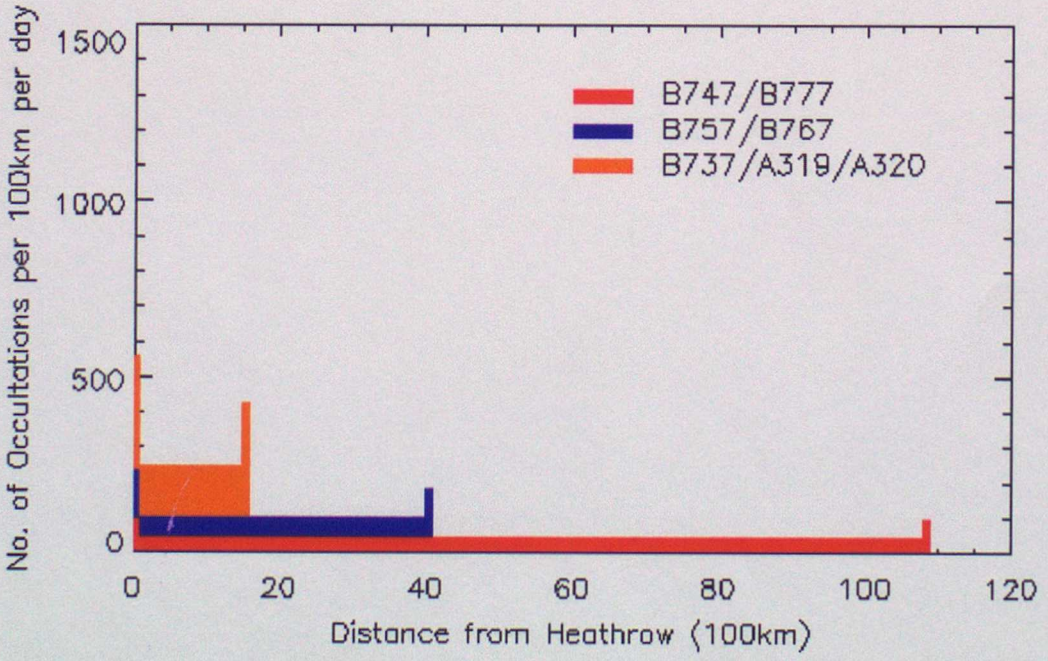

Figure 1b. As figure 1a but assuming minimum number of flights per day

2.2 Assimilation

Assimilation is the process whereby measurements of various meteorological parameters are combined with a previous forecast to provide the initial conditions for a new forecast.

2.2.1 Sources of upper air data available to models

NWP models need data defining both conditions near the earth's surface and conditions well away from the earth's surface - so-called upper air. Upper air data at present come from three quite distinct sources: radiosondes, aircraft and satellites. Radiosondes measure temperature, humidity and wind, and are in general launched from major centres of population (although in addition considerable efforts are made to obtain coverage of the more remote parts of the world). In general they are funded by the national meteorological service covering the country from which they are launched. Aircraft measure temperature, wind and, up to a point turbulence (see section 3.6) and provide coverage of most of the major air routes used worldwide, particularly those in the Northern Hemisphere extra-tropics. Funding arrangements vary enormously worldwide; for example, there is a Europe-wide funding agency (EUCOS- the European Composite Observing System) but in addition individual countries fund data transmission, e.g. South Africa, Australia. Satellite data come from both polar orbiter and geostationary satellites. The polar orbiters largely provide soundings of temperature and humidity, plus more restricted information on liquid water content. Geostationary satellites provide wind data by tracking either clouds or anomalously humid patches of air. Satellite programmes are in general funded by either a single country (eg USA, Japan) or a small continent (eg Europe).

Humidity information from radiosondes is relatively accurate (by comparison with other sources) but the limited coverage is a major limitation. Humidity information from satellites has good coverage but poor accuracy and rather limited vertical resolution. The latter is a distinct limitation as far as predictions of both fog and icing are concerned. In contrast, GNSS/aircraft humidity data will have good vertical resolution but poor resolution in the along line-of-sight direction.

2.2.2 The error covariance length scale

The errors in an assimilated field are a function of the errors in the measurements, the distribution of the measurements, and the errors in the previous forecast. The method used by many NWP centres is called Variational Assimilation, and for this method it is possible to derive quite rigorous relationships between the errors in the assimilated field as a function of the errors in the input variables. A critical concept is that of an error covariance length scale.

In variational assimilation, the spatial variation of the influence of a measurement is a strong function of the background error covariance function. That is, if the error covariance has a long length scale, then a measurement will affect the assimilated field a long way from the position of the measurement, whereas if the length scale of the error covariance is shorter, the measurement will only affect the assimilated field locally. It follows that in order to assess the likely impact of an additional source of humidity profiles, one needs to consider the density of the additional profiles in the context of the covariance length scales. It is reasonable to argue that if the density of profiles is much less than one per covariance length scale then it is likely that increasing the density would lead to a significant improvement in the accuracy of the assimilated field. However, if the density of profiles is of the order of one per covariance length scale then it is unlikely that increasing the density would lead to any significant improvement in the accuracy

The humidity error covariance length scale for the Met Office global model is quoted as lying between 179 km and 199 km (Ingleby 2001, table 2). For the European Centre for Medium Range Weather Forecasts system, it lies between 252km and 290 km (Rabire et al, 1998, table 2). For the Met Office mesoscale model, the figure is 90km (Renshaw, 2001, private communication). The mesoscale model would be the one used to provide

forecasts of fog and thunderstorms for UK airports such as Heathrow. The model extends approximately 1500 km away from Heathrow in all horizontal directions (this is a very approximate statement as Heathrow is not in the middle of the domain). The significance of the 1500km is that that is also where the highest density of occultations will occur for a UK based operator such as BA, according to figure 1b. What this means is that, ignoring anisotropy, for the whole of the mesoscale model domain there would be 240 occultations per 100km radial distance from the hub airport. For these purposes the covariance length scale of 90km is close enough to the 100km figure used to derive the density of occultations. The annulus with a radius of 1500km and width 100km has a circumference of about 10000 km so the 240 occultations per day that occur within the annulus give rise to approximately 2.4 occultations per day per 100km gridbox. Thus every covariance lengthscale gridbox has at least 2 occultations per day. Although the mesoscale model is run 4 times per day, in order of magnitude terms it is clear that data from a combined fleet comparable in size, utilisation and proportion of different aircraft types to the BA combined fleet, will give sufficient occultations to adequately define the humidity field in a model comparable to the mesoscale model.

To conclude on this section, it is fair to say that if the distribution of data was isotropic and if BA data were the only source of GNSS/humidity data for forecasting for Heathrow, then the quantity of data available would very closely meet the requirements. That is, the data available are, quantitatively, "just right", as opposed to "slightly less than desired", or "more than enough". Subject to the considerations in section 2.4, halving the data available would significantly degrade the forecast, but doubling the data available (e.g. by getting data from other operators using Heathrow) would have a much smaller effect on accuracy. However, the anisotropy is a significant issue - it can be assumed that none of the B737s will be flying westwards from Heathrow so in this direction the data coverage will be less than requirements. In addition, for the purposes of forecasting it is in general desirable to have more data upwind of the location for which the forecast is required. The further work required to address this issue is covered in section 5.

2.2.3 Increased impact with the introduction of 4-D Variational Assimilation

The version of variational assimilation currently used in the Met Office is 3-dimensional. Measurements made within a particular time window are used to provide the best estimate of the initial state of the atmosphere at some time roughly in the middle of the time window. No use is made of information obtained from pairs of measurements at the same location but different times to infer the time rate of change of atmospheric variables. This information is potentially quite valuable. For example, the dominant mechanism for changing relative humidity in the free atmosphere (as opposed to the part of the atmosphere close to the earth's surface) is vertical motion. If air moves upwards, its relative humidity will increase, and conversely. Therefore a pair of measurements of the relative humidity of air at the same location but different times can be used to infer (quantitatively) the vertical motion.

With 4-D variational assimilation the time dependency in measurements can be exploited, as suggested above. With 3-D variational assimilation humidity measurements will by-and-large only affect the humidity field, but with 4-D variational assimilation the vertical motion field (and subsequently, the wind and mass fields will also be affected). Thus the impact of extra humidity profiles will be greatly magnified once 4-D variational assimilation is run operationally. This is likely to be implemented at the Met Office within the next 5 years.

It should be emphasised that the data used by 4-D variational assimilation will be identical to that used currently. At present the latest data overwrites earlier data, but after implementation the *differences* between the latest data and the earlier data will be exploited.

2.3 Forecast

NWP models are extremely complex so, by comparison with assimilation, it is more difficult to say what the impact of improved humidity fields is likely to be. A large number of studies of the impact of additional data have been performed - a recent bibliography of such studies had over 300 entries. It is therefore very difficult

to draw reliable, general conclusions from these studies. Most of these studies considered the effect of additional data on forecasts, which is a combination of the effects of the data on the assimilated field and the effects of the modified assimilated field on the forecast. However, because in this current study we are considering those two processes separately, we had to choose (somewhat arbitrarily) where to include the results of these studies.

2.3.1 Summary of more relevant papers

Zapotocny et al (2000) conducted a so-called data-denial investigation - for a single forecast various forms of data were removed and the impact assessed. Of the 34 data types tested, 7 'are shown to be among the most statistically important in terms of overall impact'. These 7 include radiosonde temperature and relative humidity (one type) and vertically integrated precipitable water from satellite sensors (two types). Thus the implication is that in general humidity information has a strong impact which is comparable with some other currently available data types. However, many other data types had significantly less impact.

Amstrup and Modensen (2000) conclude that "Humidity data are essential if automated aircraft data are to replace some radiosonde stations close to airports".

2.3.2 Impact of improved humidity on other predicted parameters

Initially in a forecast the impact of any modification to the humidity field will only be felt in the humidity field. However as soon as condensation occurs there will be an impact on temperature and this will, in due course, affect all the other variables in the model. One of the prime variables of importance to aviation is wind (see section 3.5). It has to be said that the impact of improved humidity on wind is likely to be noticeable only relatively late in the forecast, particularly in the extra-tropics, quite possibly on timescales longer than the 18hours which is assumed to be the length of the longest commercial flight. However, it must be remembered that each assimilation is preceded by a forecast which produces the initial guess - there is a chain of forecast/assimilation cycles. Therefore improved humidity data in one forecast could well improve the accuracy of later forecasts of other parameters, such as wind. For example, if in a single forecast improved humidity data starts to have a positive effect on wind after 24 hours (a plausible timescale for high latitudes), then a forecast issued 24 hours after the one having the improved humidity data could well have improved wind accuracy on the timescales of value to civil aviation.

2.4 The optimistic view

If it is assumed that

(a) GNSS/aviation humidity profiles will be as accurate as low earth orbit satellite GPS data
(b) Current error covariance functions reliably represent the real covariance in model errors
(c) The dominant source of error in forecasts of the parameters of importance is the initial conditions
(d) Within the measurable initial parameters, the one with the biggest error is humidity
(e) Errors in vertical motion will be significantly reduced through improved instantaneous humidity fields and the implementation of 4-D variational assimilation

Then it follows that there will be a dramatic improvement in the forecasts of parameters of importance through the availability of large numbers of GNSS/aviation humidity profiles.

It is very difficult to prove that any one of the assumptions is false - there is significant uncertainty in many of them. However, in the absence of clear proof that one of the assumptions is wrong, it is reasonable to conclude that there may well be a dramatic improvement.

2.5 The conservative view

Given the uncertainty associated with each of the assumptions, it is sensibly cautious to assume that any of the assumptions may be seriously wrong and that therefore the impact of the GNSS/aviation humidity profiles is

likely to be small. A consequence of this view is that further research is conducted with the aim of reducing the uncertainties associated with most if not all of the assumptions.

3 Forecast Products

3.1 Contrails

3.1.1 Significance of contrails for civil aviation

As was mentioned in the introduction, there is increasing concern about the effect of aviation on the environment (IPCC, 1999), in particular the possible effects of contrails and cirrus cloud sheets that might grow from these. There is uncertainty about the magnitude of the effect of contrails on the top-of-atmosphere radiation balance. It is well understood that contrails at night will have a relatively strong adverse effect on climate change whereas the effect of contrails during the day is much harder to quantify.

In 2001, the UK Met Office was asked a number of questions by the then UK Department of Environment, Transport and the Regions, concerning the environmental impacts of aircraft. One of these questions was: "If economic instruments were used to reflect the polluter pays principle, should such instruments be varied in relation to the sensitivity of location or operating time (for example for night flights)?"

The Met Office response was "Any system of fines should reflect the adverse effect of aviation on the environment, and in general that is a function of time and place. Therefore there should be financial penalties for night flights which do not apply to day flights. The designation "night flight" would depend on the average value of the local solar zenith angle, averaged along the whole flight."

Whilst avoidance of flying at night would significantly reduce damage to the environment, the operational consequences for airlines would be severe (for example, a significant increase in the number of aircraft required to maintain transatlantic services). An alternative option would be to fly routes during the day which spatially are chosen to minimise the likelihood of contrails. The disadvantage of this approach is that the distance flown (and therefore the CO_2 output) is likely to be increased. The penalty is minimised if forecasts of the locations in the atmosphere where contrail occurrence is likely are very accurate.

3.1.2 Sensitivity of contrail forecasts to meteorological parameters

At a particular flight level, the occurrence of a contrail depends on both temperature and humidity (and also on characteristics of the aircraft engine - see Moss (1999)). However, the dominant source of error is the humidity. Therefore improved assimilated fields of humidity are likely to give rise to improved forecasts of contrail occurrence, particularly for short range forecasts, and particularly if 4-dimensional variational assimilation is implemented.

At low levels in the atmosphere variation of refractivity is largely due to variations in humidity. However, at aircraft cruise levels, temperature effects become significant.

Scott et al (2001) performed a comprehensive study of verification of contrail forecasts using NWP data. They identified "borderline" situations, when slight changes in the input data could alter the forecast outcome, and non-borderline situations, which could be reliably forecast up to 24 hours ahead. It is clear that GNSS data could add significantly to our ability to handle the borderline cases. We reproduce the part of table 2 from Scott et al which shows the sensitivity of the difference between the critical temperature and the actual temperature as a function of temperature and relative humidity, at 300hPa (~FL300). If this temperature difference is negative, contrails will occur: if it is positive, they will not. We also show the refractivity that would occur at this combination of pressure, temperature and relative humidity.

		RH= 0%	RH=25%	RH=50%	RH=75%	RH=100%
T=-43.0	$T-T_c$	6.73	4.97	3.20	1.44	-0.33
T=-43.0	Refractivity*100	101.15	101.39	101.62	101.85	102.09
T=-44.5	$T-T_c$	5.23	3.74	2.24	0.74	-0.76
T=-44.5	Refractivity*100	101.82	102.02	102.22	102.42	102.62
T=-46.0	$T-T_c$	3.73	2.47	1.20	-0.07	-1.33
T=-46.0	Refractivity*100	102.49	102.66	102.83	103.00	103.18

What this table shows is that knowing the refractivity locally to the working requirement of 0.5% (see section 2.1.1) will contribute significantly to our ability to forecast these borderline cases. What is particularly encouraging is that $T-T_c$ is a monotonically increasing function of the refractivity, regardless of whether temperature or relative humidity is varied. For other applications of GNSS/aviation data the so-called water vapour ambiguity (see, for example, Healy and Eyre, 2000) limits the utility of the data unless other information is available to resolve the ambiguity.

Further work would be required to quantify the volume of the atmosphere that these borderline cases occupy, and hence the effect of improved contrail forecasts on flight practices.

3.2 Icing

Icing occurs when an aircraft flies through a supercooled cloud (that is, a cloud comprising water drops, when the ambient air temperature is below zero). More specifically, the surface temperature of aircraft components needs to be below zero for icing to occur on that component. The maximum rate of icing depends on the liquid water content: the actual rate of icing depends on the dropsize distribution and factors which depend on the aircraft.

3.2.1 Significance of icing for civil aviation

Turbofan powered aircraft are equipped with anti-icing equipment which can cope with liquid water content values that are to be found anywhere except in the middle of a severe thunderstorm (which would normally be avoided because of turbulence considerations). However the operation of the anti-icing equipment requires engine power and thus causes additional fuel burn. Frequently the equipment is operated when not strictly necessary. In addition, deployment of anti-icing will slow the aircraft when in either ascent or descent, adding an extra variable to be considered in 4-dimensional trajectory prediction.

There is an additional consideration for twin engined aircraft flying long distances over water (ETOPS operations). For fuel loading purposes, consideration has to be given to the scenario in which the aircraft loses the use of an engine, loses cabin pressure and has to fly to a diversion airfield in icing conditions at an altitude of about 10000 feet. This consideration sometimes forces the aircraft to carry extra fuel. If icing conditions could be forecast reliably, then it is reasonable to argue that the regulations should be changed to allow less fuel to be carried when icing was not forecast.

Turboprop powered aircraft are usually equipped with de-icing equipment which can cope with conditions provided it is operated at the right time, which is often difficult for the pilot to establish. There have been a number of accidents in which icing of turboprops has been a contributory factor so it is reasonable to assume that the accident rate could be reduced through improved forecasts, provided the operators have confidence to use them.

General aviation aircraft have varying degrees of protection from icing, and many aircraft have no protection at all and should not be flown in known icing conditions. Clearly for these operators improved forecasts could have significant benefits, allowing some combination of improved availability of the aircraft or improved safety levels.

3.2.2 Sensitivity of icing forecasts to meteorological parameters

Many NWP models cannot explicitly predict supercooled liquid water content. However, the Met Office mesoscale model can, (a version of the global model which can is expected to be introduced within the next 12 months). Significant work will be done to validate the forecasts produced by the global model, but our experience with the mesoscale model is disappointing (Brown, 2000). Consequently, current practice is to base icing forecasts on forecasts of relative humidity and temperature: if the temperature lies between certain threshold values, and the relative humidity exceeds a threshold value, then it is forecast that icing will occur. As with contrails, the dominant source of error is humidity, so again improved assimilated fields of humidity are likely to improve forecasts of icing occurrence, particularly for short range forecasts, and particularly if 4-dimensional variational assimilation is implemented.

3.3 Fog

3.3.1 Significance of fog for civil aviation

The significance of fog depends critically on the level of equipment both on the aircraft and at the destination airport, together with the training of the crew. For an airline such as British Airways and an airport such as Heathrow, Category 3b operations are now possible for most aircraft in the fleet, so it is extremely rare for a diversion to be required simply because of the instantaneous conditions. However, when low visibility procedures come into effect, which happens when category 2 conditions occur, the landing rate is reduced to approximately one third that of which applies in VMC (Visual Meteorological Conditions). Therefore there is a serious impact on flow, and this can happen at any European airport. The reduction in landing rate is necessary in order to protect the ILS (Instrument Landing System) localiser: in the future if GNSS systems become the prime source of navigation information, this sensitivity may be greatly reduced.

For less well equipped aircraft, fog is a much more serious problem - turboprops typically vary between having a category 2 capability and having no autoland capability at all. For them, therefore, the chance of being forced to undertake a diversion is proportionately greater. For GA (general aviation) aircraft the problems are even greater. In the UK, meteorological problems were the biggest cause of fatal GA accidents in the 1990s. Within the meteorological factors, controlled flight into terrain in poor visibility was the biggest causal factor.

3.3.2 Sensitivity of fog forecasts to meteorological parameters

Fog occurs wherever the visibility falls below the relevant threshold. Visibility is a function of the liquid water content. So if icing forecasts can be assumed to be likely to improve, so will fog forecasts. However, the quality of GNSS/aircraft humidiy data at very low level is questionable, so the impact may well be reduced. Work has been done to establish the sensitivity of fog forecasts to changing the input parameters. Clark and Hopwood (2001) conclude that "the greatest impact on the forecast evolution of including in-situ observations was provided by the inclusion of humidity measurements". The other measurements considered were wind (both speed and direction) and temperature, in the boundary layer. It is worth adding that a major source of error in forecasts made with this model is cloud sheets either forming over the airport in question or being advected (transported by the wind) into the area of importance. Improved humidity data in the upper air (again possibly coupled to improved knowledge of the vertical motion field, through 4-D variational assimilation) will address this.

3.4 Thunderstorms

3.4.1 Significance of thunderstorms for civil aviation

Whilst it is true that thunderstorms do not have the impact in Europe that they do in the USA, the sensitivity in Europe is a strong function of latitude. Even so, on occasion the impact of thunderstorms on airports such as Heathrow can be significant. It has been shown (Hoad, 1999) that our skill in forecasting thunderstorms as they affect en-route traffic, is extremely limited and has very strong time dependency (i.e. whilst we might have some skill in forecasting 1 hour ahead, there is hardly any skill 3 hours ahead). For flow management activities, several hours warning is highly desirable.

3.4.2 Sensitivity of thunderstorm forecasts to meteorological parameters

Much work has been done with models designed specifically to forecast thunderstorms, which in general terms are not in operational use. For example, Ducrocq et al (2000) considered the initialisation of a fine-scale model for the prediction of convective systems. They conducted a number of experiments and concluded that the largest sensitivity was found for the initial amount of moisture introduced in the initial state. Admittedly, the parameters investigated were rather limited, but the likely sensitivity of the forecast outcome to input relative humidity is confirmed.

3.5 Other products (except turbulence)

As was mentioned in section 2.3.2, the prediction of all parameters in a forecast model should improve as a result of introducing improved humidity data. Winds, temperatures, precipitation and cloud can all be expected to improve, although it is impossible to say by how much. This means that the prediction of fronts will improve. However, it is stressed that fronts do not, as such, constitute a hazard to aviation. The representation of fronts on Significant Weather charts is controversial with the aviation community and unpopular with the meteorological community. It is believed that they are included so that in the event of an en-route diversion, the pilot has information to hand pertaining to the weather conditions at the diversion airfield. In an era of rapid digital communication with the cockpit, the value of this type of information is diminished. However, the factors which could lead to an en-route diversion might also affect communications, so the pilot is justified in requiring information on the flight deck.

It is also worth stating that many of the hazards that do affect aviation are associated with fronts, particularly icing and, to a lesser extent, thunderstorms. However these hazards have been addressed explicitly earlier in this report.

3.6 Turbulence

The specification of work requested a brief description of the benefits to turbulence forecasting when measurements of turbulence on board aircraft are available. It should be made clear that, through the AMDAR (Aircraft Meteorological Data Relay) mechanism, measurements of vertical acceleration are currently available from large numbers of aircraft, particularly those flown by European operators. The reporting does have its limitations - the vertical acceleration of the aircraft is reported in one of only 4 categories (corresponding very roughly to no turbulence, light turbulence, moderate turbulence and severe turbulence). More sophisticated algorithms are available, including those which calculate Eddy Dissipation Rate, although further work is required to clarify the appropriate timescales on which the algorithm should be applied.

Unlike humidity, turbulence is not a prognostic variable in NWP models. If/when turbulence is required to be forecast, it is diagnosed from prognostic variables in the model. It follows that it is much more difficult to estimate the impact of quantitative turbulence data on NWP than is the case for one of the prognostic variables such as humidity. Given the uncertainties in the latter (see section 2.4) it is considered impossible within the resources allowed to quantify the benefits for turbulence data.

Turbulence is not a persistent phenomenon, except where it is associated with mountain waves. Therefore the availability of high quality turbulence reports in real time is of limited value in helping to improve turbulence nowcasts. The fundamental requirement is for a research capability that facilitates the diagnosis of the cause of turbulence on a case-by-case basis. For example, in many cases even clear air turbulence is associated with convection, which can be identified from satellite imagery. Ultimately a system for nowcasting turbulence would place heavy reliance on satellite imagery. At the present time it is difficult to say exactly how reliable such a system would be.

It is worth stating that it is desirable to get turbulence data on a more continuous scale than the 4 categories currently used. However, it is not clear that benefits are likely from employing sophisticated algorithms such as Eddy Dissipation Rate, compared to the much simpler Equivalent Vertical Gust. A possible exception to this is the use of such data to predict the behaviour of wake vortices.

It is possible that the mechanism constraining the accuracy of GNSS/aviation humidity data is turbulence, as it is unlikely that it will be possible to determine the velocity and/or position of the aircraft with sufficient accuracy to determine the refractivity in highly turbulent conditions. It will be necessary to use numerical turbulence data from aircraft to quantify this problem properly, but there is no need in the short term for the data to be promulgated to the ground in real time in order to do this.

4 Conclusions

The fundamental conclusion is that it is very difficult to make quantitative statements about the impact of GNSS/aviation humidity data. It is possible, if one is optimistic about the validity of a set of five assumptions, that the impact of the data is highly significant. However, if any one of the five assumptions is not strictly true, then the impact will be reduced.

However it is possible to draw conclusions about the quantity of data available. It appears that, if data were available from the main classes of aircraft within the BA fleet, that this would be sufficient to define the humidity field in the Met Office mesoscale model. This model is used to forecast thunderstorms and fog, among other parameters, at airports such as Heathrow.

It is also concluded that GNSS/aviation data will contribute significantly to our ability to forecast contrails. Given the concern about the effect of aviation on the environment, particularly the effects of contrails and the cirrus cloud sheets that might grow from these, this improvement is potentially valuable. It would mean that aircraft can fly routes which are very close to those which minimise the adverse impact on the environment.

5 Recommendations for future work

The fundamental recommendation is that further work is carried out to reduce the uncertainty in the five assumptions listed in section 2.4. Within the Met Office, to a greater or lesser extent, work is already planned to address the uncertainties in the last four assumptions. Therefore the top priority for additional, currently unplanned work is for flight trials to be conducted which quantify the likely accuracy of GNSS/aviation humidity data. The results of a relatively small number of flight trials might be inconclusive, so a parallel activity would need to be an assessment of the response of aircraft to the range of turbulence that occurs in the atmosphere. This would use accelerometer data from civil aircraft to quantify the frequency of turbulence levels in the atmosphere.

The complexity of any flight trials should not be underestimated. The ideal configuration would involve two aircraft, one to measure the GNSS data and a second to make measurements that validate the retrieved profiles. The GNSS data could for example be obtained by the Qinetiq BAC 1-11, whilst the validation data could be obtained by dropping dropsondes from the Met Office BAe 146. Thus a single flight trial would cost well in excess of €10000. Of the order of ten flight trials would be required. After that some reasonably robust

conclusions could be drawn (if the flight trials go well), ideally for a specification for a GNSS data reception configuration for a commercial aircraft.

Additional GNSS antennae would have to be fitted to the GNSS aircraft, which might be a non-trivial exercise which would attract extra cost. It is suggested that guidance should be sought from Qinetiq as to the likley costs involved.

In addition it is desirable to explore the space-time geometry problem, that is, generate a four-dimensional version of figure 1. This is considered lower priority than the flight trials, but it is probably a less expensive activity. In this study we have considered a single operator and a single hub airport. There are of course many operators and many hub airports within Europe. Data from BA would be sufficient for forecasting for Heathrow, and contribute to improving forecasts at airports such as Frankfurt. The four dimensional study would determine the overall requirement from all operators to cover the needs of all the major European airports.

6 Appendices

6.1 Appendix 1 - the derivation of figures1a and 1b

The figures are constructed using data about the British Airways fleet that was extracted from the BA web site on 22nd October 2001.
The basic data used were in the following table:

Fleet type	B747/B777	B757/B767	B737/A319/A320
Number in fleet	97	69	81
Utilisation in hours per day	12	9	7
Maximum number of flights flown per day	2	6	8
Minimum number of flights flown per day	1	2	4

Note that the numbers in the fleets and the utilisation figures are derived from the BA data. The minimum and maximum flights per day are informed guesses based on some limited knowledge of BA operations.

The number of landings per day is equal to the number of flights flown per day multiplied by the number of aircraft in the fleet.

The length of flight is equal to the utilisation multiplied by the speed (assumed to be 900 km/hour for all fleets) divided by the number of flights flown per day.

The number of occultations per 100km per day for the en-route phase is the number of aircraft in the fleet multiplied by the utilisation multiplied by the speed multiplied by the number of occultations per 100km for a single aircraft divided by the length of the flight.

The number of occultations per 100km for a single aircraft is assumed to be 0.42, based on the fact that for a Paris/New York flight 25 occultations were generated (Lesne and Haase, 2001).

It is assumed that there will be one extra occultation per ascent and one extra per descent. This is based on a simple geometrical calculation using the number and orbits of GPS satellites. It should be regarded as an order of magnitude estimate. It is possible that the quality of occultation data obtained during ascent and descent will not match that taken during the cruise phase. However, in drawing conclusions about the density of available data, occultations taken during ascent and descent have been ignored.

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8 Acronyms

AMDAR	Aircraft Meteorological Data Relay
A319	Airbus 319 (an aircraft type - an A320 is another Airbus type)
BA	British Airways
B737	Boeing 737 (an aircraft type - B747, B757, B767 and B777 are other Boeing types)
EUCOS	European Composite Observing System
GA	General Aviation
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
ILS	Instrument Landing System
NWP	Numerical Weather Prediction
VMC	Visual Meteorological Conditions